ISSN 0040-6015, Thermal Engineering, 2014, Vol. 61, No. 4, pp. 295–302.

STEAM-TURBINE, GAS-TURBINE, AND COMBINED-CYCLE PLANTS AND THEIR AUXILIARY EQUIPMENT

Experience Gained from Using Water and Steam for Bringing the Operation of Aircraft- and Marine-Derivative Gas-Turbine Engines in Compliance with Environmental Standards

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Abstract—Practical experience gained from using water and steam admission into the combustion chambers of aircraft- and marine-derivative gas turbines for bringing their operation in compliance with the requirements of environmental standards is described. The design and schematic modifications of combustion chambers and fuel system through which this goal is achieved are considered. The results obtained from industrial and rig tests of combustion chambers fitted with water or steam admission systems are presented.

Keywords: gas turbine, combustion chamber, injection of water and steam, emission of harmful admixtures
DOI: 10.1134/S0040601514040028

The currently implemented and prospective (up to the year 2030) plans for renovating and developing the Russian power-generating capacities foresee wide use of gas turbine units (GTUs), which is mainly due to high efficiency of combined-cycle power plants (CCPs) constructed on the basis of GTUs. Modern power-generating CCPs have an efficiency of 57–62%, which is a record high indicator for fossil-fueled installations. CCPs operate in the main on natural gas, which is the most valuable fuel. However, for Russia with its huge resources of gas, this strategy is justified in many respects. Another positive feature of CCPs is a low extent to which they pollute the environment.

The relevant Russian environmental standard imposes quite stringent limitations on the permissible concentrations of NO_x in the exhaust gases from GTUs. Efforts that are being taken with the aim to reduce NO_x emissions are mainly focused at developing an environmentally friendly combustion chamber (EFCC) for GTUs, which is far from being a trivial task. Its complexity lies in the fact that, on one hand, a few contradictory requirements connected with securing full-valued and stable combustion in the chamber must be fulfilled and on the other hand, conditions must be set up for reducing the generation of NO_x and producing a homogeneous gas flow in the combustion chamber in all modes of GTU operation. Development of an EFCC involves great material expenditures; therefore, a large number of scientific and industry branch institutes are engaged in this work apart from gas turbine companies.

The task of developing an EFCC becomes significantly more difficult when aircraft and marine GTUs are adapted to be used for power-generating purposes, because the problem of bringing them in line with the environmental standards has to be solved subject to some additional constraints. In view of compact overall dimensions of the initial combustion chambers used in the engines being adapted for power-generating purposes, the gas flows in them have high velocities, and the combustion chambers themselves are characterized by a highly thermally stressed working volume, which entails both incomplete combustion of fuel and an increased level of NO_x emissions. The scope of modifications aimed at adapting an aircraft or a marine GTU to power-generating purposes does not involve any change in the overall dimensions of the combustion chamber for the reason of retaining expensive components of the sealed GTU casing, which serve, among other things, for aligning the rotor system supports and keeping integrity of the engine power circuit arrangement.

For bringing GTUs being adapted for power-generating purposes in compliance with the environmental safety requirements, significant design and schematic changes must be made both in the combustion chamber itself and in the GTU fuel equipment and automatic control system. The cost of introduced modifications is quite high: the price of a GTU with an EFCC and without it may exceed the price of the initial GTU by more than 20%. The growth of prices is especially appreciable in the case of applying so-called "dry" combustion chambers, devices intricate both in

the design and automation respects. They are usually installed in large-capacity stationary GTUs, and lean fuel–air mixtures are fired in them.

The set of research works that was carried out by the authors on using water and steam in EFCCs opens the possibility to considerably reduce the expenditures for development and construction of an EFCC. Positive experience gained with suppressing NO_x emissions by means of water and steam in different types of GTUs makes the elaborated methods to a certain extent universal in nature.

In works dealing with "wet" EFCCs, the effect of water and steam on different components of the combustion chamber and on the entire GTU was studied, including the fuel equipment and exhaust path, and water treatment issues were analyzed.

Studies of water injection at the inlet to the GTU compressor for increasing the GTU power output showed that the use of this measure also leads to certain reduction of NO_x emissions. A similar effect is obtained when water is injected in between the compressor stages and when steam is injected into the combustion chamber [1, 2]. The greatest reduction of NO_x emissions is achieved by injecting water and steam into the combustion chamber burning zone. A positive effect is obtained in these cases as a result of decreasing the gas temperature in the burning zone and ballasting the combustion products by steam. The determining role of temperature in the generation of nitrogen oxides is described in detail in the combustion theory of Ya.B. Zel'dovich. So-called "thermal" nitrogen oxides, which comprise the major mass of oxides, are generated from the totality of reactions, which become essentially more intense at temperatures above 1600°C.

The rate of reactions is a factor that is of much importance for achieving complete combustion of fuel in the flow. This process slows down as the gas temperature in the burning zone decreases, and incomplete combustion (appearance of CO) and unstable combustion may take place at excessively low temperatures in this zone. A noticeable growth of CO concentration is observed at temperatures below 1500°C.

If we wish to ballast the burning zone in a rational manner, the objective should be formulated in a more exact way: it is necessary to reduce the temperature in local hot zones of the combustion chamber without hampering subsequent final oxidation of CO in the flow. Zones characterized by the stoichiometric fuel-to-air ratio, i.e., with the air excess factor α close to unity, are examples of such local hot zones. In the diffusion-type combustion chambers of aircraft or marine GTUs adapted for power-generation purposes, the volume in which combustion takes place may contain quite a number (sometimes more than 10) of such discrete zones. The necessary amount of steam or water can be admitted to these numerous zones while avoiding excessive cooling of zones with $\alpha > 1$ by uniformly mixing ballast with fuel, i.e., by making a homogeneous mixture.

Injection of water into the burning zone is a more universal ballasting method, because steam with the necessary parameters is available only in a CCP or if the existing thermal power stations are topped with a gas turbine. Water can be injected into the combustion chamber burning zone in several ways. The simplest one of them is to inject water through the fuel nozzle (Fig. 1). Mechanical atomizing of water through a nozzle (Fig. 1a) requires, like spraying of liquid fuel, considerable expenditures of energy, because quite high outflow velocities are required to obtain the necessary water spraying dispersity, and up to 10 MPa pressure has to be applied for achieving this. It should be noted that the water admission system has a rather short service life due to its intense erosion. In addition, possible impact of water on the combustion chamber hot elements may give rise to dangerous effects.

Pneumatic (aeration) nozzles can be installed, which produce somewhat finer atomizing than mechanical nozzles do, but they consume more power.

Wide use of the described methods for atomizing water in the combustion chamber is limited due to the cost of water system itself and the cost of its operation. Injection of superheated water with its subsequent flashing gives finer atomization but involves more problems with its operation.

Unfortunately, none of the described water spraying versions ensures sufficiently uniform mixing with fuel and distribution over the burning zone.

Better atomization of water and its mixing with the fuel–air mixture can be achieved by using the hybrid burner developed by Siemens, in which the energy of air, steam, or gaseous fuel itself is used for the above-mentioned purposes [3]. A similar design solution was used by specialists of MMPP Salyut in modernizing the DTs-59 engines for installing them at the GTU-based RTS-4 cogeneration station of MOEK in Zelenograd, Moscow oblast.

Two-channel fuel nozzles were installed in the DTs-59 engine combustion chamber (Fig. 2), and water was supplied through them directly into the burning zone. Diffusion combustion, which is traditionally used in aircraft engines, is organized in the chamber. The combustion process is stabilized by means of an annular angle stabilizer of the front device swirler and by generating return vortices in the primary burning zone A. During operation at parameters close to the nominal ones, the average values of air excess factor in these zones are equal to 0.5–0.2 and 2.6–2.2, respectively. The burning zone length from the swirler

to the plane of secondary air admission holes (mixing air) in the flame tube is 500 mm. The time for which gas dwells in this primary zone is 3–6 ms. Intense evaporation of water and suppression of NO_x emission by the produced steam occur in the primary zone within a so short period of time owing to the developed surface of water droplets. The necessary dispersity of water with droplets having an average diameter of less than 50 μm is obtained by using a mechanical nozzle with a built-in centrifugal screw in combination with pneumatic (aeration) atomization of water in the swirler by gaseous fuel in the nozzle and by air.

Tests of the modernized DTs-59 engine carried out by MMPP Salyut specialists showed that the combustion chamber operates efficiently at the flow rates of water in a mixture with gaseous fuel equal to 1.2–1.6 of fuel flow rate. However, attempts to maintain NO_x emissions at the required level entailed a considerable growth of CO emission. The stable operation range of the EFCC with water injection becomes significantly wider during operation on liquid fuel; however, some additional problems arise in this case.

As is known, different kinds of liquid fuels are used in power engineering applications: diesel fuels, dedicated gas turbine fuel, and heavier products, e.g., petroleum gas oils. The technical requirements for liquid fuels specify the maximal content of water, which has been determined primarily from the considerations of ensuring reliable operation of the fuel supply system. Water is contained in fuel in the form of suspension or emulsion, and as a rule, its concentration should not exceed 1.5%, which is much smaller than the amount of water admitted into a GTU for suppressing NO_x emission. This limitation is stemming from the need to preserve integrity of high-precision pairs used in the fuel-pumping equipment and to exclude possible corrosion of fuel system elements. The stability of combustion in the combustion chamber itself may also be upset if water plugs emerge in the fuel supply path. Thus, we can infer from field experience that in mixing liquid fuels with water for bringing the combustion process in compliance with the environmental standards, reliable homogeneity of the mixture without its stratification into components must be ensured in an exceptionally careful manner. Experience gained from introducing anticorrosion additives into gas turbine fuel in the M-25 marine gas turbine installation can bring certain gain in this respect.

Gas turbine fuels have an increased content of vanadium and sulfur, which has a negative effect on the turbine service life due to accelerated corrosion of the blade system. Admixtures of sodium and various solid particles contained in the fuels also have an unfavorable effect on gas turbine engines and fuel equipment. The methods for removing these drawbacks are

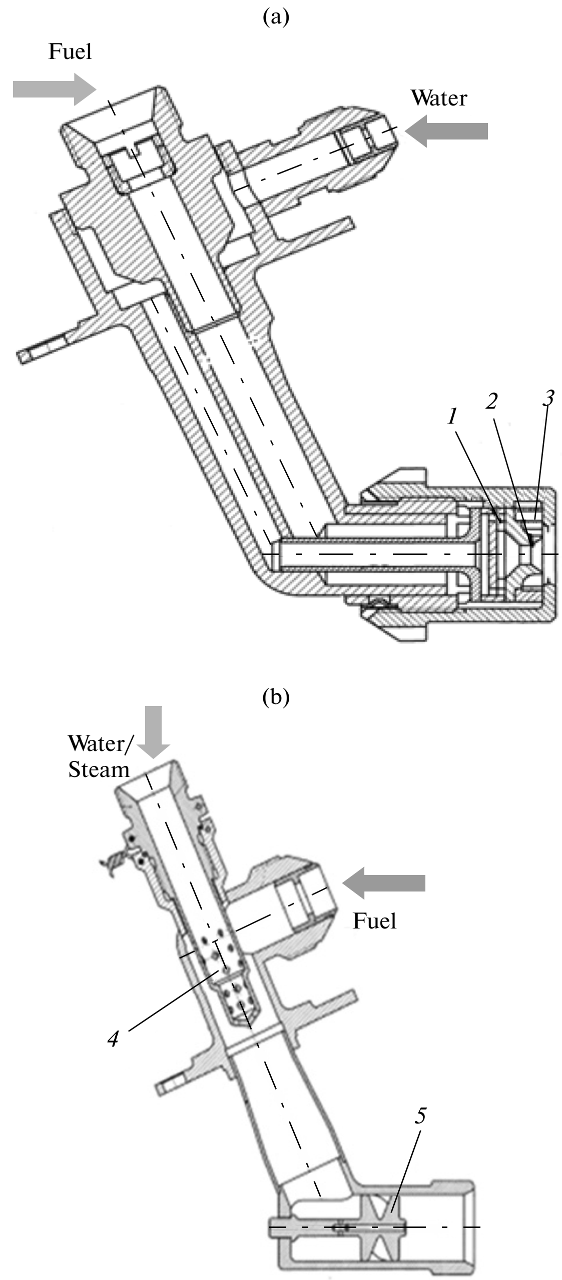

Fig. 1. Water–fuel nozzles. (a) Nozzle for natural gas with mechanical water spraying, (b) the same with aeration water spraying; (*1*) screw, (*2*) nozzle, (*3*) swirler, (*4*) splitter, and (*5*) swirling screw.

well known [4]. The fuel is washed with water, which is then separated together with the sodium dissolved in it and with some solid inclusions. After that, an additive preliminarily mixed with fuel is introduced into the gas turbine fuel (by means of a metering device) that prevents high-temperature vanadium and sodium-sulfide corrosion of the turbine flow path. The NIMB-2 additive [made according to TU (Technical Specifications) 38USSR 301230-80], which is the most widely known

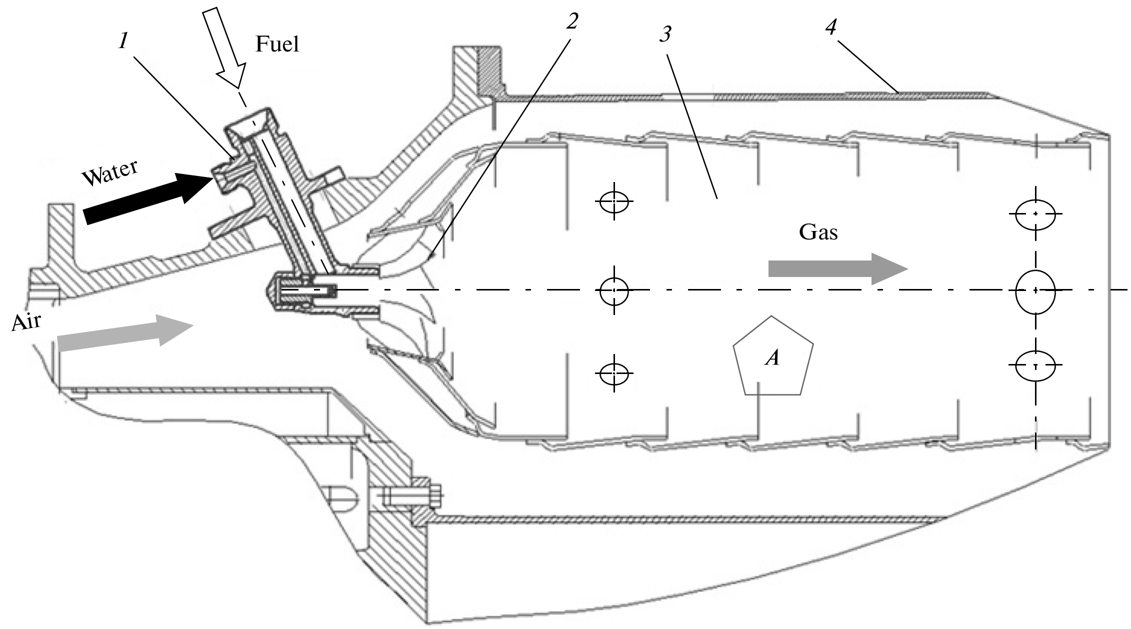

Fig. 2. DTs-59 engine combustion chamber with water admission into the burning zone through the fuel nozzle. (*1*) Water–fuel nozzle, (*2*) flame tube front device swirler with an angle stabilizer, (*3*) combustion chamber flame tube, (*4*) combustion chamber sealed casing.

agent of this sort in Russia, is a mixture of acid magnesium, chromium, and ammonium salts of synthetic fat acids C3–C6 and has the form of transparent dark-green liquid with a flash temperature of 90°C.

The described process arrangement of the M-25 gas-turbine unit was used in the experiments carried out with the "wet" EFCC of a marine-derivative GTU. A preliminarily homogenized water-fuel emulsion was added to the fuel by means of a metering device. A slit-type homogenizer was used for preparing the emulsion, which had a sufficiently high pressure difference of more than 10 MPa. The first experience gained from operation of the GTU according to the above-described arrangement with a homogenizer revealed essential drawbacks. The main problem was concerned with securing reliable operation of the fuel equipment. For ensuring intactness of the equipment, it was necessary to include an algorithm for carefully washing it with pure fuel, because the emulsion was susceptible to stratification during its long-term storage, and water behaved as corrosive agent with respect to fuel equipment components.

Stratification of water and fuel in the header entailed inadmissible increase of nonuniformity in the gas temperature field downstream of the combustion chamber. Free water appeared in fuel when attempts were made to homogenize fuel with a large amount of water (more than 50% of fuel flowrate). The need to keep high pressure in the homogenizer entailed a growth of energy expenditures for the GTU auxiliaries and had a detrimental effect on the service life of equipment units.

The content of water in fuel is decreased with decreasing the GTU load. A large length of the pipeline filled with watered fuel results in that flame extinction in the flame tube is sometimes observed during a drastic drop of the GTU power output.

The above-mentioned operational difficulties are eliminated when the water admission point is shifted behind the fuel control valve to a point immediately upstream of the fuel header. In this case, it becomes possible to use a homogeneous water-fuel suspension having a less stable composition. Such homogeneous mixture can be prepared in a vortex-type mixer with fairly low energy expenditures. Unlike other devices (ultrasonic generators, mechanical and cavitation homogenizers), vortex mixers do not require an external source of energy; they are reliable and do not have moving elements. Vortex mixers use the working fluid flow energy for their operation. The permissible pressure difference is quite moderate (0.1–0.2 MPa), and the suspension going out from the mixture remains stable for a sufficiently long period of time. The use of such devices allows reliable operation of GTUs to be maintained with fuel containing water in an amount required for suppressing NO_x generation. With water supplied in a ratio of 0.8 to the fuel flow rate, the concentration of harmful NO_x emissions in the spent gases from a GTU can be reduced by a factor of 5 or in absolute terms down to 100 mg/m^3 (when recalculated for standard temperature and pressure).

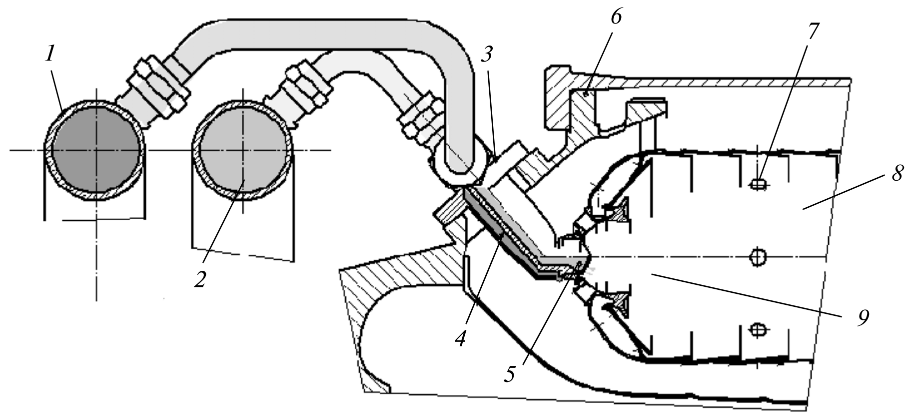

Fig. 3. Combustion chamber with steam admission into the burning zone through the fuel nozzle. (*1*) Steam header, (*2*) fuel header, (*3*) steam–fuel nozzle, (*4*) steam channel in the nozzle, (*5*) gaseous fuel channel in the nozzle, (*6*) combustion chamber sealed casing, (*7*) secondary air holes, (*8*) flame tube, and (*9*) flame tube front device swirler.

The effectiveness of using water in GTUs for suppressing NO_x emissions should be considered concurrently with other effects connected with water injection into the combustion chamber burning zone, which allows a higher power output to be obtained from the gas turbine unit at the specified values of temperature upstream of the turbine. At moderate concentrations of water (up to 60% of fuel flow rate), liquid fuel can be combusted more completely [5] as a result of additional atomization of sprayed fuel droplets due to flash-like boiling of dispersed evaporating water.

It should also be borne in mind that discharge of steam with spent gases from the GTU results in a loss of a large amount of energy in the engine thermodynamic cycle in the form of latent heat of vaporization. The effect from using a “wet” EFCC must be estimated with due regard of the above-mentioned circumstance. Heat losses may be quite significant, and they must be brought to an acceptable minimum, first of all, through the use of suitable schematic solutions.

In the majority of cases, implementation of process and thermodynamic solutions aimed at fulfilling one of the main objectives pursued in constructing GTUs, namely, compensating energy losses with spent gases, entails complication of the GTU design. A search for efficient solutions is carried out on the basis of technical–economic calculations. One of such solutions is to inject steam into the GTU path, which is generated by using the heat of spent gases, including the so-called “environment protection” steam that is used instead of water to suppress NO_x emission [6].

The following power facilities can serve as examples of efficient use of a “wet” EFCC with steam injection: the GTU-based PGU-52 combined-cycle plant at the Elets cogeneration station, the Vodolei GPA-16K gas pumping unit at the Stavishchinsk gas-pump station in the Ukraine, and the PGU-60S combined-cycle plant at Mosenergo’s TETs-28 cogeneration station incorporating the features of test grounds.

Central to all these projects is the idea of making a power facility that combines arrangements for returning the waste-gases energy into the power generation cycle and ensuring environmental friendliness of CC operation.

In the EFCC of the GPA-16K unit, as in the EFCC of the PGU-60S installation, steam generated in the heat-recovery boiler is supplied through the fuel nozzle. Such an admission arrangement differs from that used in the DTs-59 engine design in that steam is preliminarily mixed with air upstream of the front device swirler, after which is it mixed with fuel itself in the front device (Fig. 3). In the DTs-59 engine combustion chamber, the ballast (water) was first mixed with fuel and then with oxidizer. Tests of a few engines showed that in case of steam admission into the burning zone with premixing it with air upstream of the swirler, the optimal steam to gaseous fuel (methane) flow rate ratio is in the range 1.2–1.6. This ratio corresponds to the minimal level of NO_x emissions with an insignificantly increased level of CO emission and is valid for combustion chambers with the air temperature downstream of the compressor equal to 400°C, and with the design of the front device with a swirler similar to that used in the DTs-59 engine (see Fig. 2) modified taking into account certain specific features of air flow aerodynamics. This mainly concerns the velocity and direction of the incident air flow attacking the flame tube front device. A series of experiments involving determination of the chemical composition of air in the head part of flame tubes used in different GTUs was carried out, and it was found from these experiments that straight-flow combustion chambers

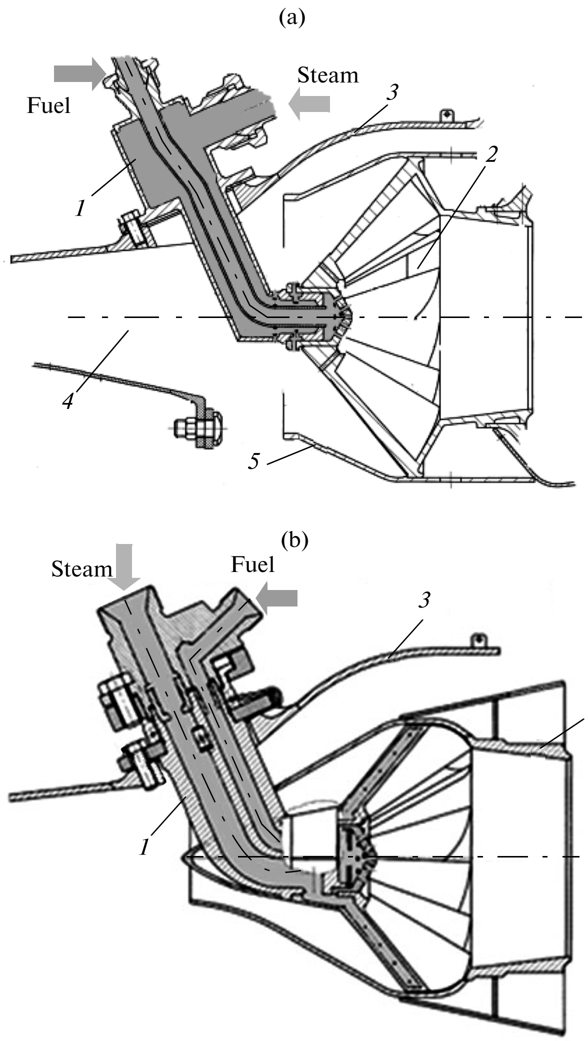

Fig. 4. Versions of front devices used in straight-flow EFCCs operating on gaseous fuel with steam injection. (a) Before modification of the steam admission assembly, (b) after modification of the steam admission assembly; (*1*) fuel nozzle, (*2*) swirler, (*3*) sealed casing, (*4*) diffuser, and (*5*) flame tube intake-fairing device.

are characterized by considerably nonuniform filling of the swirler channels. Zones of back air flows from the swirler to the shell space are observed in such combustion chambers in the front device region upstream of the flame tube inlet. As a result, an attempt to use a solution for the straight-flow combustion chamber of the aircraft-derivative AL-21 engine similar to that applied for the loop-type combustion chambers of the GPA-16K Vodolei and PGU-60C installations (Fig. 3) (according to which steam is admitted in the region of the swirlers of these combustion chambers) led to an increased content of CO and unburned hydrocarbons at the turbine outlet. This phenomenon occurred because part of steam ejected from the nozzles entered into the flame tube cooling system and into the primary air blast holes and because the fuel afterburning process took a longer period of time.

Figure 4 shows the versions for organizing steam admission to the flame tube front device in the AL-21 engine with modifications aimed at excluding carryover of steam beyond the front device boundaries. The use of steam admission directly from the nozzle upstream of the swirler similar to that implemented in the PGU-60S unit failed to ensure complete mixing of steam with fuel and air in the front device, even though there was a shortened intake fairing (see Fig. 4a). Moving opposite to the main air flow, this steam partially entered into the shell space and then to the flame tube cold zones with a high value of air excess factor, thus aggravating incomplete combustion in the combustion chamber. A radical solution of this problem is shown in Fig. 4b.

Preliminary mixing of steam with gaseous fuel allows deeper suppression of NO_x emissions to be achieved as in the case of mixing water with liquid fuel. Calculations show that for highly thermally stressed combustion chambers with an air temperature downstream of the compressor higher than 500°C (the compression ratio $\pi_c \geq 21$), an increased steam to air flow rate ratio equal to 3 is the optimal one.

An EFCC in which steam is premixed with gaseous fuel was implemented in the project of adapting the AL-21 engine for the PGU-52 combined-cycle plant at the Elets cogeneration station. In the PGU-2 installation, the "environment protection" steam was mixed with fuel upstream of the fuel header (Fig. 5).

One specific feature of the implemented system was that it contained a steam ejector, which served to ensure reliable mixing of media (fuel gas and steam) at the nozzle inlets and to create increased gas pressure upstream of the nozzles, thus facilitating control of the combustion process and operation of the automatic control system. The idea of multipurpose usage of ejector in such systems seems to be quite fruitful.

At the Elets cogeneration station, steam for the GTU was extracted from the common-station steam header and had the following parameters at the GTU inlet:

Pressure, MPa	3.9
Temperature, °C	440
Flow rate, t/h	4–10

The engine operating parameters during the tests are given in Table 1, and the technical data of the ejector in three modes of system operation are given in Table 2.

Since the volume flow rate of steam–fuel mixture is a few times higher than that of fuel, nozzles and fuel headers with an increased flow pass section are used in

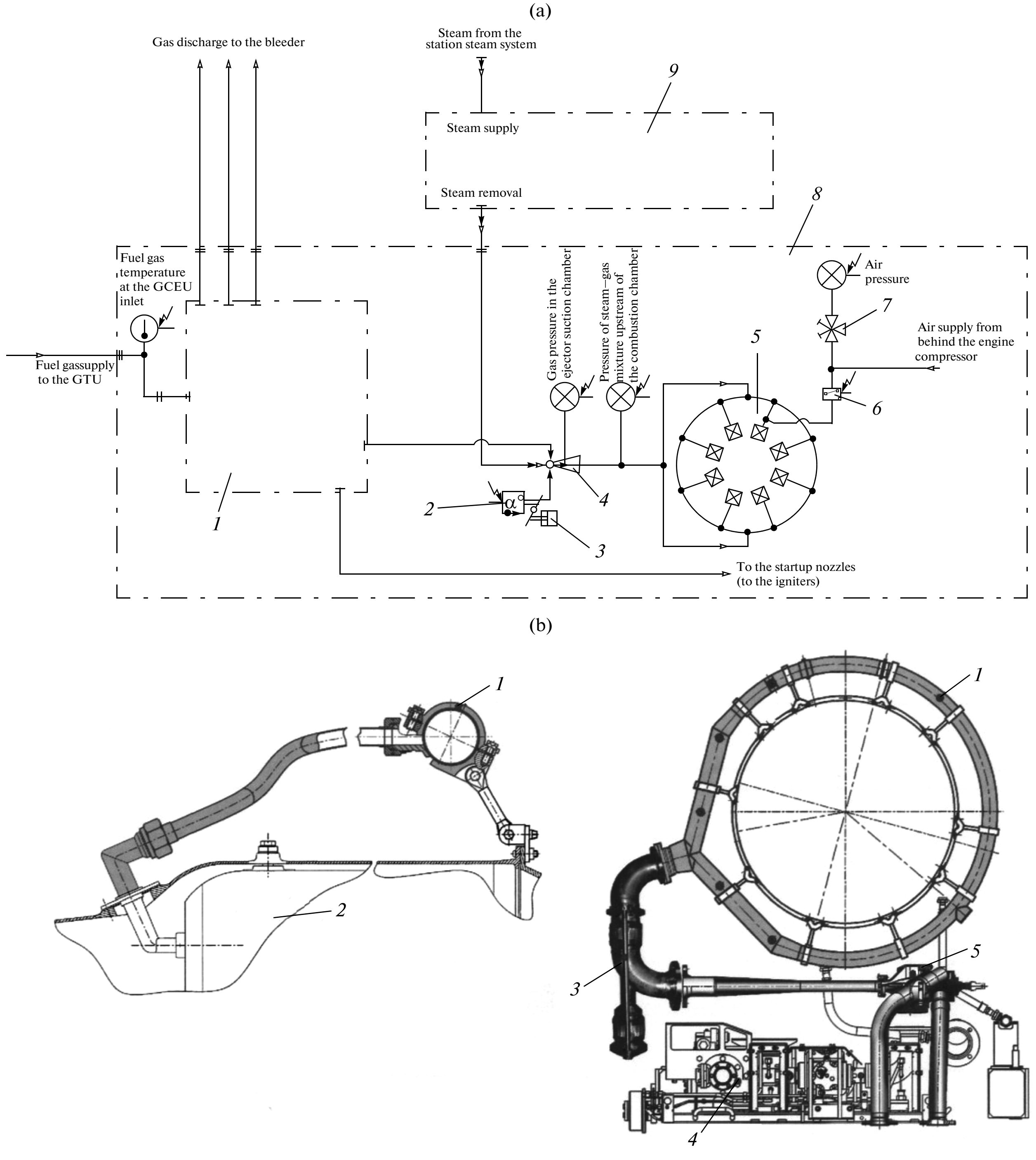

Fig. 5. Fragment of the fuel system schematic arrangement of the PGU-52 combined-cycle plant's GTU with a steam ejector. (a) Basic design arrangement: (*1*) gas control equipment unit (GCEU), (*2*) rotation angle sensor, (*3*) ejector control hydraulic cylinder, (*4*) ejector, (*5*) engine fuel header, (*6*) nozzle pressure difference relay sensor, (*7*) purging coke, (*8*) GTU container unit, (*9*) steam admission unit; (b) illustrative schematic diagram: (*1*) steam–gas header, (*2*) combustion chamber, (*3*) compensation unit, (*4*) GCEU, and (*5*) ejector.

the project. The required flow rate of steam–gas mixture is obtained at a pressure upstream of the header up to 2.53 MPa, which cannot be achieved with the fuel system available at the station.

The results of PGU-52 tests [7] recorded a considerable drop of NO_x concentration in flue gases in case of using a steam–gas mixture. In view of moderate air temperature downstream of the compressor, no higher than 400°C ($\pi_c \geq 11$), NO_x emission not exceeding

Table 1. Parameters of engine during the tests

GTU power output, MW	Fuel flow rate, kg/h	Steam flow rate to the EFCC, t/h
Less than 12	3150	0
No less than 12	3100	4.2
15	3750	5.5
20	4550	7.8
25	5210	10.0

Table 2. Technical data of the ejector

Working medium	Flow rate, kg/h	Pressure, MPa	Temperature, °C
Natural gas at the ejector inlet:			
mode 1	3250	0.85	40
mode 2	4300	1.25	40
mode 3	5470	1.90	40
Steam at the ejector inlet:			
mode 1	4200	3.65	440
mode 2	6900	3.65	440
mode 3	10000	3.70	440
Steam–gas mixture at the ejector outlet:			
mode 1	–	1.35	–
mode 2	–	1.86	–
mode 3	–	2.53	–

50 mg/m^3 (at standard temperature and pressure) is obtained already with steam to air flow rate ratio equal to 1.2.

Thus, the experience gained from the implemented projects of "environmentally clean" combustion chambers of aircraft- and marine-derivative GTUs confirms the effectiveness of using steam and water as a means for suppressing NO_x emission.

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Translated by V. Filatov